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Experimental Study on Surface Characteristics of Inconel 718 Sheets Cutting with Nitrogen - Assist Laser Beam

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Abstract:

Laser cutting of Inconel 718 sheets allows substantial cost savings as compared to traditional sawing, milling and drilling. The quality of the cut surface is more affected by a few operations, including cutting speed, cutting gas pressure, and laser output power. Additionally, the type of gas for cutting also plays a significant role in achieving a clean edge. In this work, Nitrogen gas is used in laser beam cutting. It not only helps to blow away molten metal but also ensures no reaction at the cut surface and no dross adhesion. Therefore, it is possible to obtain a clean edge, and it avoids subsequent cleanup process. This paper focuses on an experimental analysis of the Inconel 718 sheets' surface roughness which were cut by Nitrogen gas (N_2) assisted laser beam with 13 bar pressure and 2.4 to 4.5 kW range power laser cutting system. Characterization of Inconel 718 sheets before and after laser cut was studied by using SEM analysis with conjunction of Energy Dispersive X-ray (EDX). The hardness of the material was also accomplished by using Rockwell Hardness Tester.

Introduction:

Inconel 718 is used to create a range of components. Because of its outstanding mechanical and chemical qualities at high temperatures it is used in important industries like nuclear power plants, aerospace, and the marine and chemical industries. (Akca and Gürsel, 2015). Although Inconel 718 possesses high strength, creep resistance and good thermal stability, there is much difficulty in cutting of this material due to its poor machinability. The machinability of this alloy is mainly influenced by its low thermal conductivity, toughness and strain hardening.

Inconel 718 specifically experiences plastic deformation, adhesion to cutting tools, limited dimensional stability, shortened tool life, poor surface polish, and high production costs during the manufacturing process (Paturi et al., 2021; De Bartolomeis et al., 2021). In order to address these drawbacks to a certain possible extent laser cutting technologies have been employed for manufacturing of mechanical components made of Inconel super alloy sheets. Primarily the laser cutting technology offers high processing speed, smooth cutting and simple programming (Radovanovic, M., & Madic, M. (2011).

One of the most sophisticated sheets cutting techniques is laser beam cutting (LBC), which is better suited for tough-to-cut sheet materials. LBC is basically a non-contact, highly automated thermal based cutting process. A coaxial jet of assisted gas flow is required to force the melting metal out of the cutting zone. (Chau, 2019). LBC is a complex and non-uniform process as choosing the right laser and process parameters directly affects the standard of the cut surface of Inconel 718 (Shrivastava, P. K et al., 2020). In this context, numerous attempts have been documented. Dong-Gyu et al. (2009) Studies on cutting Inconel 718 have been done and the findings indicate that the speed of cutting is examined how cutting settings effected thermal properties and kerfwidth development when cutting Inconel 718 sheets with a CW Nd: YAG laser. They observed kerfwidth and slope of the cut section in the practical cutting regions fell between the ranges of were 0.53-0.61 mm and $80.4^{0} – 86.6^{0}$ respectively. According to experimental findings of Nyon et al. (2012), as laser power increases, the kerf width improves, and as cutting speeds increase, it decreases. Hasçalık and Ay (2013) conduct an experiment utilized a 4-kW power and continuous CO_2 laser cutting system and evaluate kerf taper ratios, surface roughness, and recast layer thickness (RLT) of age-hardened Inconel 718. It indicates that cutting speed, assisted gas pressure, and laser power have a huge impact on RLT. According to Shrivastava and Pandey (2018), a hybrid approach involving multiple regression analysis and genetic algorithms was used in the laser cutting of Inconel-718 optimize the kerf taper,kerf deviation and kerf width. They aimed to pinpoint to improve cutting quality, accuracy, and precision and developed a robust prediction model and validated it by comparing the predicted values with the outcome of the experiments carried on cutting of Inconel 718 on 300 W pulsed Nd: YAG laser cutting system. In addition to cutting parameters, assist gas also plays a crucial role in achieving cut quality. The pressure gradient and the frictional force gas cause melt ejection to happen. If the molten metal is not appropriately removed from the cut zone, the surface finish of the cuts will deteriorate (Chen et al., 2001). The production of striations and dross on the cut surface might result from incorrect pressure settings for the assist gas.

Assist gas selection and pressure maintenance must be done with care since they have a greater impact on cutting efficiency and cut surface quality. When materials are thicker, higher gas pressures are frequently necessary. The commonly used assist gases are oxygen, nitrogen, argon and helium. The desire for cutting efficiency and the quality of the cut surface often determines the gas choice. If the cut surface quality is not essentially required for mild steel, oxygen gas can be used. Titanium and titanium alloys should only be laser cut using an inert atmosphere, preferably argon gas. (Rao et al., 2005 & Kovalev, O. B., 2009). In the case of laser beam cutting of Ni-based alloys, nitrogen (N_2) gas is the most preferred one instead of oxygen, as it eliminates dross formation at the underside of the cuts. To ensure no reaction taking place at the cutting zone and to avoid much cleaning after laser cutting, N_2 gas may be an appropriate choice for LBC of Inconel 718 super-alloy sheets (Dubey, A. K., & Yadava, V, 2008 and Sharma, A., & Yadava, V, 2018). In the present experimentation study N_2 gas has been used as assist gas in LBC of Inconel 718. The current work focuses on the examination of Inconel 718 sheets using Energy Dispersive X-rays (EDX). before and after cutting, hardness test, Scanning Electron Microscope (SEM) analysis and observing surface roughness at specific range of laser power (2.4 kW - 4.5 kW), cutting speed (5.5 m/min – 6.5 m/min) and constant plate thickness (2mm), nitrogen gas pressure (13 bar).

Experimentation:

Laser Cutting of INCONEL 718 sheets:

To research laser cutting surface properties of Inconel 718 sheets, DNE laser cutting machine was used. Laser beam is employed to gently vaporise, melt, and remove material.

In CNC laser cutting, a guiding system, an assist gas, and optics are commonly utilized to focus and direct the laser beam onto the work piece. This ensures precise and controlled cutting of the material. Compared to traditional techniques, CNC laser cutting offers several benefits. Indeed, laser beam cutting is a non-contact method ideally suited for advanced materials like brittle, hard, electrically conductive, non-electrically conductive, soft, and thin materials. Secondly in addition to being a thermal process, laser cutting can effectively handle materials with high thermal characteristics, irrespective of their mechanical properties. This feature enables successful treatment of such materials, enhancing the versatility and applicability of laser cutting across various industries and applications. Thirdly, the method is flexible. Additional advantages include minimum surface and metallurgical deformation, little material loss, straight edges, low surface roughness, and furthermore, laser cutting has the benefit of being simple to integrate with computer numerically controlled (CNC) machinery, which makes it possible to precisely cut elaborate patterns. This seamless integration streamlines the manufacturing process, enabling efficient production of complex designs with high accuracy and repeatability (Radovanovic, M., & Madic, M. 2011). In this experiment, the aided gas is nitrogen (N_2). When oxygen and moisture react chemically with the metal, oxidation occurs, resulting in corrosion. By employing nitrogen in the cutting process, any nearby oxygen is kept from interacting with the metal and no additional heat is generated. Depending on the thickness and strength of the metal being cut, higher nitrogen pressures are required. Preventing metal oxidation results in a higher-quality finish and cuts down on the time it takes to prepare for welding and surface treatment after cutting. To avoid any inconsistencies in the cut, the laser cutting procedure requires a clean laser beam stream.

The Inconel sheet is 250 mm length and 150 mm breadth and thickness of 2mm is used for cutting with laser beam cutting system. The work piece is placed on the supports as shown in Figure 1.

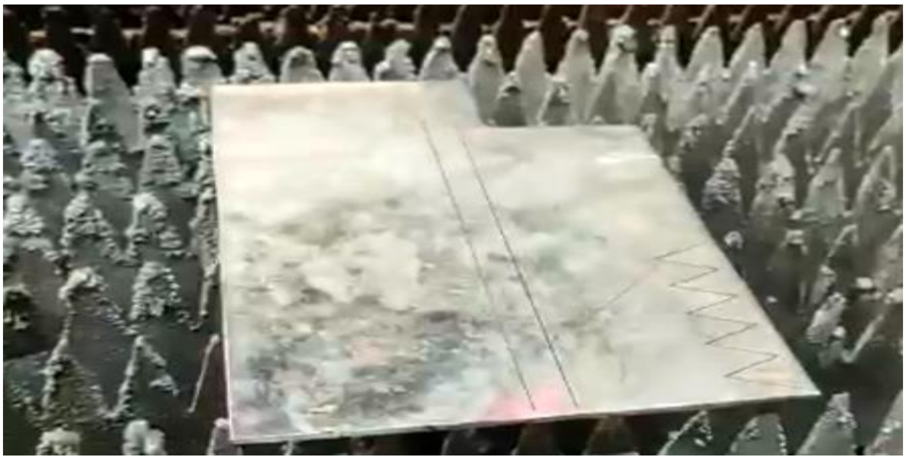


Figure 1: Inconel 718 sheet setup on equipment bed for straight and zigzag cut

In a
DNE laser machine, a high-power laser is utilized to direct the beam onto materials through optics and computer numerical control (CNC). For most procedures, a motion control system is employed to adhere to a G-code or CNC pattern ensuring precise cutting onto the material. Materials are eliminated from the beam as it travels along a predetermined route through a variety of methods, including melting, vaporisation, and chemical degradation. The laser cutting head traverses along the specified path over the sheet, removing the designated portion from the sheet. Once the localized heating, melting, and vaporization has started the machine moves the area of the material removal across the work piece to produce the cut. To determine that, during cutting, the laser beam accurately targets the specified area of the work piece and the laser beam cutting machine's nozzle position is carefully monitored and adjusted. This precise positioning helps maintain the quality and accuracy of the cut is showed in the Figure 2.

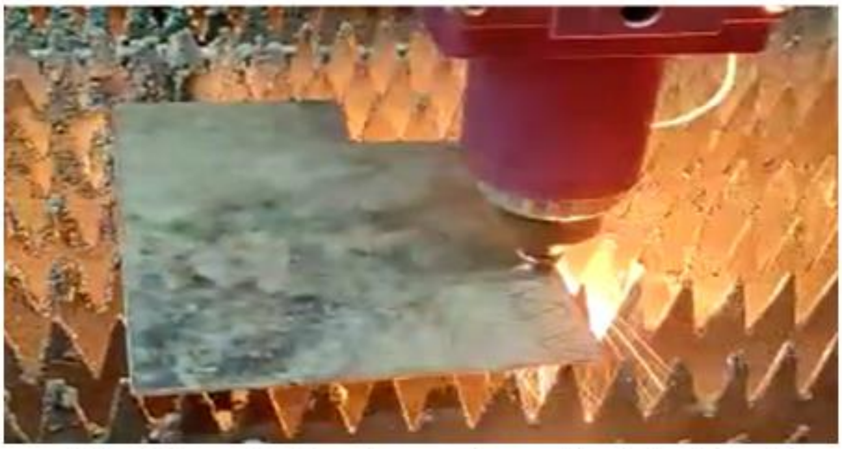


Figure 2: Position of the nozzle of laser beam cutting machine during the cutting operation

Energy Dispersive X-ray (EDX) analysis:

INCONEL 718 has undergone EDX examination both before and after laser beam cutting, and Table 1 lists the percentage of the elemental structure of each sample. Figures 3 and 4 respectively provide SEM images with a graphical representation of the percentage weight of the constituent elements for uncut and cut surfaces. The percentage of nickel reduced from 73.46 to 72.95 from the uncut surface to the surface after cutting, which is a blatant sign that extremely minute nickel compounds had formed.

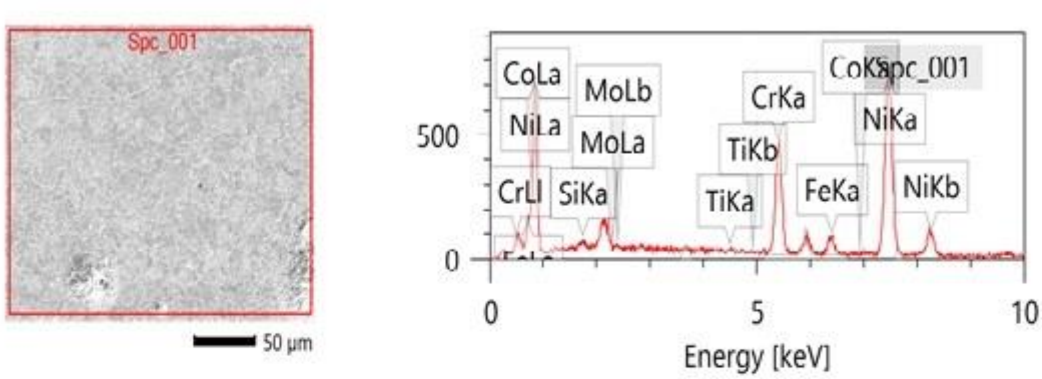


Figure 3: EDX-Analysis of surface before laser beam cutting

According to the data in Table 1, the percentage of chromium is essentially the same on cut and uncut surfaces, supporting the contention that chromium oxide (Cr2 O3) formation did not take place at a higher temperature. According to the general findings of the EDX investigation, which are shown in Table 1, the alloying components of INCONEL 718 on the surface finish remain unchanged throughout the use of a laser beam cutting aided by nitrogen gas.

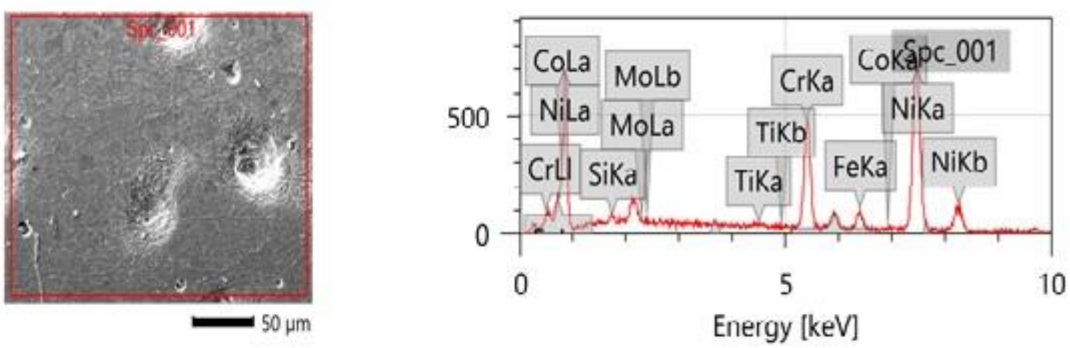


Figure 4: EDX-Analysis of cut surface after laser beam cutting

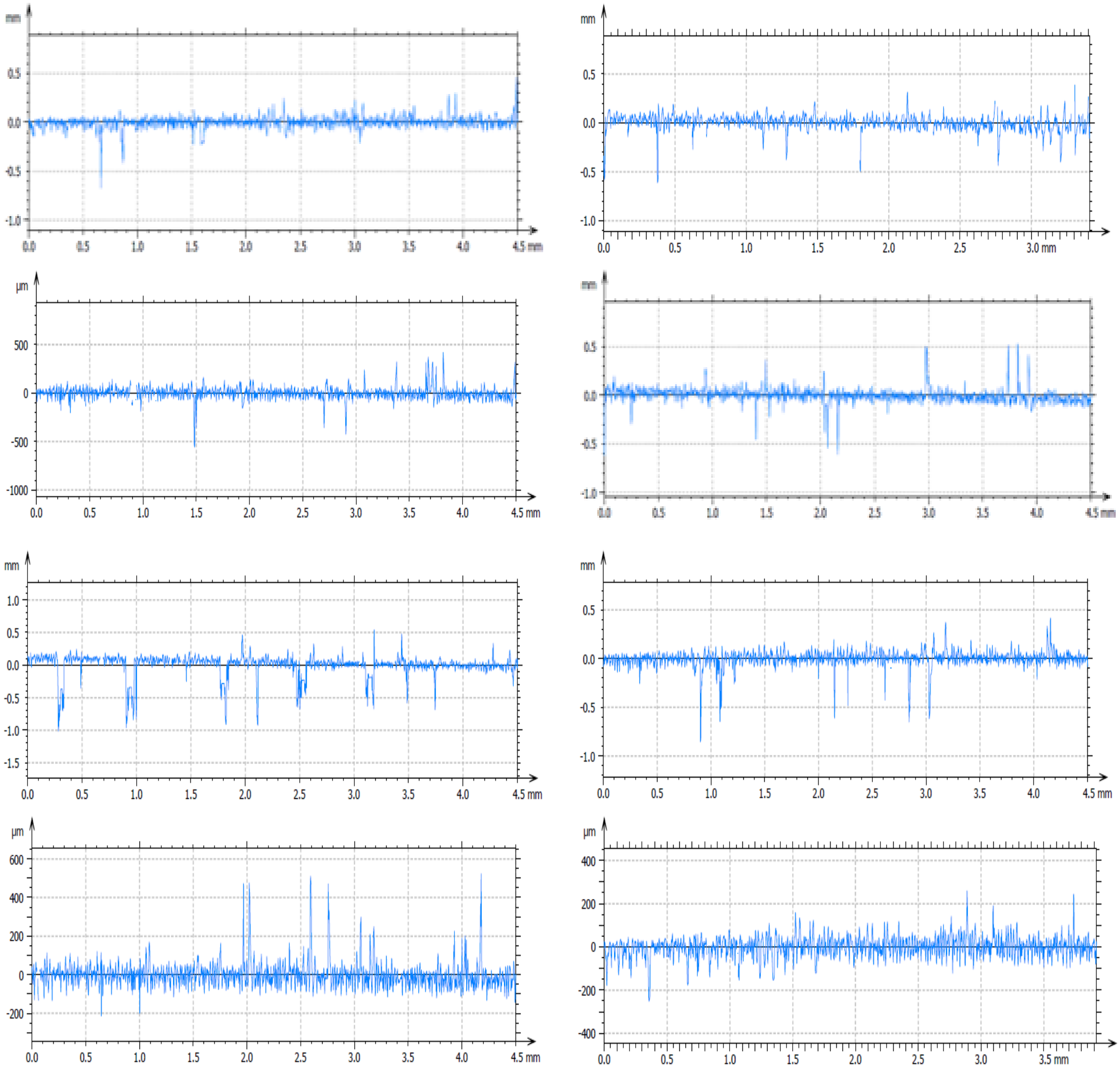
Table 1: Elemental composition of Inconel 718 before and after laser cut

Element	**Weight%**	
	Before Laser cut	**After Laser cut**
Nickel	73.46	72.95
Iron	4.35	4.68
Chromium	20.71	20.84
Manganese	0.53	0.30
Cobalt	0.05	0.40
Titanium	0.48	0.08

Silicon	0.42	0.76

Surface Roughness:

Manufacturing industries spend a lot of time and effort creating suitable surface finishes for consumer products as well as engineering components and products. Depending on their intended use, these surfaces may be either rough or smooth. Experiments were carried out in the current work using a CNC-controlled laser cutting machine. The laser's technical specifications comprise a radiation wavelength of 337 nm, with an optimal power between 2400 and 4500 W and between 5.5 and 6.5 m/min for cutting speed. The support gas utilised was N2 (nitrogen) at a constant pressure of 13 bar and plate thickness is 2 mm. Laser cutting was performed on INCONEL 718 in this experiment. Remove oil or dust from the surface of the measurement target. This process is performed using a surface roughness digital profile meter and the surface roughness is measured throughout the cutting edge's entire length. The surface profile curves at various locations along the cutting edge of the straight cut and the zigzag cut are shown in Figures 5 and 6.



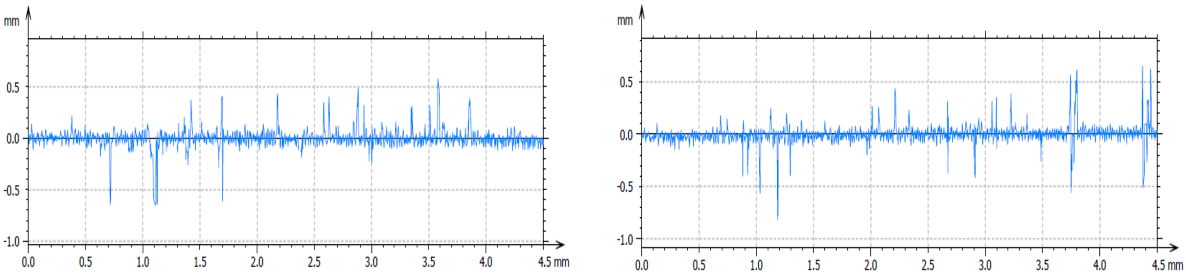
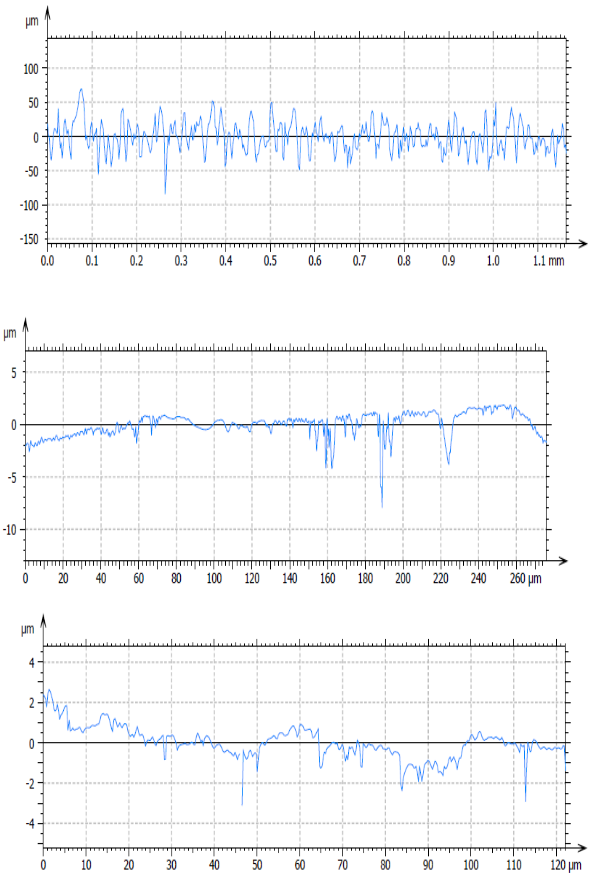


Figure 5: Surface profile curves at different locations of Straight cutting edge of INCONEL 718

According to reports in the literature (Bons, J. P. et. al., 2001 and Goodhand, M. N. et al., 2016), appropriate surface characterization requires considering several roughness factors. In industry, terms such as surface roughness is typically described in quality control using Ra (The mean height of the peaks and valleys along the centerline of the surface contour.) and Rz (average of ten-point height). While Ra is a widely used and straightforward measurement, it often aligns with Rq (RMS roughness), which reflects the profile's deviation from the mean line.

The profile’s skewness (Rsk) was then calculated. This non-dimensional value is (i) zero for a distribution which is asymmetric, (ii) favorable for a surface featuring widely distributed and higher-than-average peak heights (peak-dominated), and (iii) unfavorably to a surface exhibiting evenly distributed and near-average peak heights (valley-dominated).



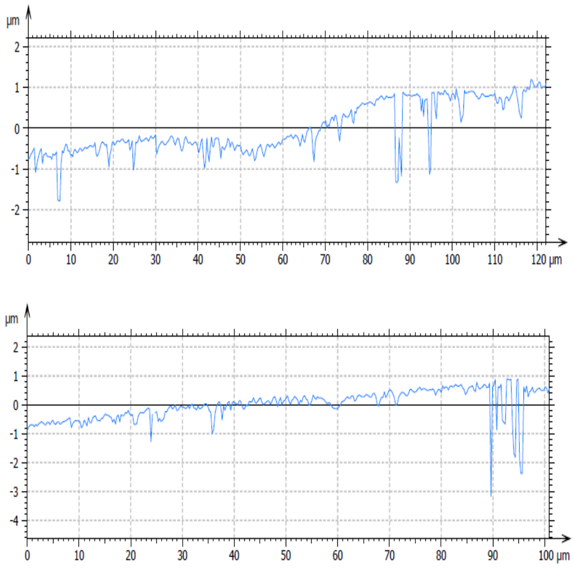


Figure 6: Surface profile curves at different locations of Zig-zag cutting edge of INCONEL 718

This measure is frequently used in literature to evaluate how surface quality affects the flow field. This classification aligns with the four Rz levels as well. (see Tables 2 and 3), which are three and four separate roughness levels that were accepted for both straight cut and zigzag cut based on the Ra values and the criteria. In simpler terms, the chosen Ra levels correspond to increasing Rz levels, indicating that the distribution of heights and peaks remains proportionate within each level. The Rsk data's figures are remarkably stable.

Table 2: Surface roughness characterization of straight cut of INCONEL 718

	Ra(µm)	Rz(µm)	Rq(µm)	Rsk (#)	Rt(µm)
Roughest	32.5	248	42.1	-0.514	383
	41.2	567	61.1	-1.29	947
	45.1	814	75.4	-0.859	137
Roughest	56.8	797	94.8	-2.44	118

Table 3: Surface roughness characterization of zigzag cut of INCONEL 718

	Ra(µm)	Rz(µm)	Rq(µm)	Rsk(#)	Rt(µm)
Smoothest	0.0978	0.766	0.140	-1.43	1.27
	0.245	1.89	0.333	-1.24	2.49
Roughest	0.550	5.09	0.796	-0.151	7.88

The standard deviation results show that the surface quality may be replicated across a broad range of target surfaces and that numerous surfaces with the same degree of roughness can be used for identical deposition experiments. The results repeatability and statistical validity are assured in this way. The peak-to-valley height is represented by the Rt values, which are reported in the final column. The roughness parameters for straight cut and zigzag cut are shown in Tables 2 and 3 in particular Ra, Rq, and Rz.

Hardness measurement by using Rockwell hardness Tester:

Hardness of Inconel super alloy sheets were measured using Rockwell hardness Tester. The Load applied on the sheet is 150kg and dwell time is 20 seconds. The 1/16'' diamond intender is used to find the hardness of the sheet. The scale used is C-scale and the value is represented by HRC. The hardness of Inconel sheet is represented in table. The hardness increases as the number of revolutions increases. The true hardness of INCONEL 718 is 40-45 HRC but the hardness of as received sheet is 37 HRC. The hardness is increase from 37 HRC to 44 HRC with increases in number of revolutions. The increasing load on the sheets leads the compression which in turn in grain refinement. The grain refinement increases the hardness value and increase in curvature along the sheet with increase in number of revolutions of INCONEL 718 sheets shows better mechanical properties during cold working. The sheets can be deformed under cold working which can be applicable in marine and aerospace applications. The Rockwell hardness test results are shown in Table 4.

Table 4: Hardness of INCONEL using Rockwell Hardness Tester

No.of revolutions	Load (kgs)	Hardness (HRC)
As received	150	37
100	150	39
200	150	40
300	150	41
400	150	44

SEM Analysis:

A scanning electron microscopy (SEM) view of an uncut surface and cut surface after Nitrogen assisted laser beam cutting of INCONEL 718 is shown in Figure 7

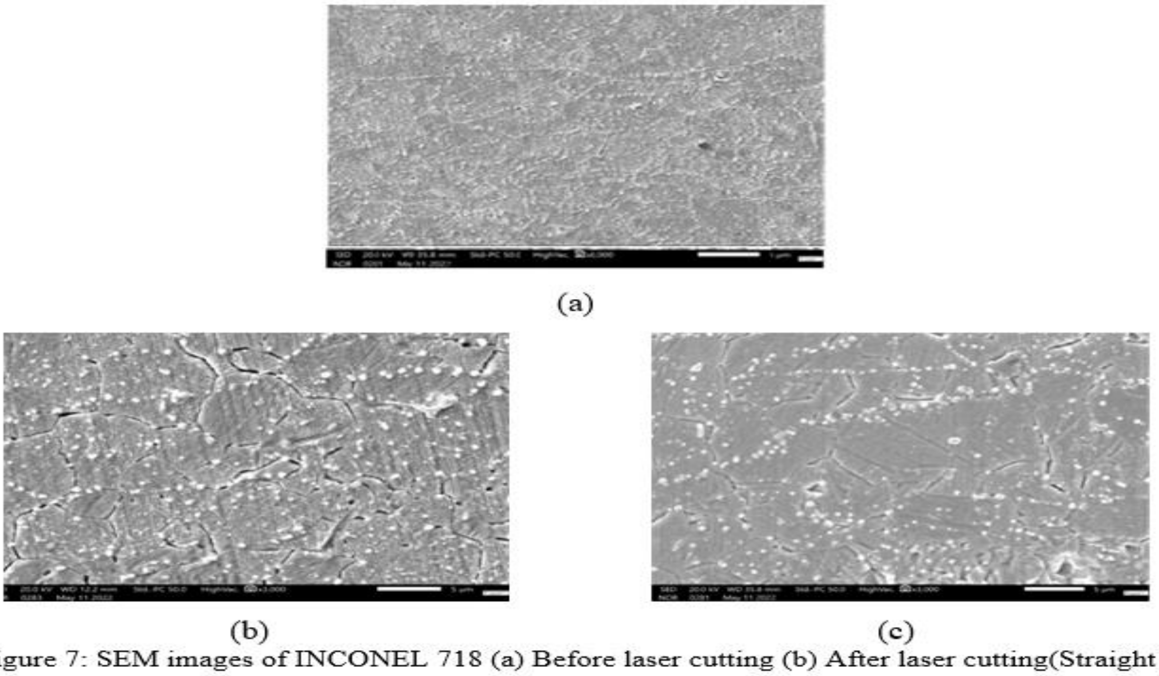


Figure 7: SEM images of INCONEL 718 (a) Before laser cutting (b) After laser cutting(Straight) (c) After laser cutting (Zigzag)

The microstructure of the cut sample differed slightly from the uncut sample after nitrogen aided laser beam cutting with laser powers ranging from 2.4 kW to 4.5 kW (Figures 7(a) & 7(b)). Under laser beam cutting circumstances, there is a chance that the surface of the white layer and the machined material will be visible. In cutting technology, a layer of this kind can be seen in the presence of high temperatures. The SEM images of the straight and zigzag cuts (Figure 7(a), (b), and (c)) clearly demonstrate the accuracy of the surface roughness measurements made by the surface roughness tester (Tables 2 and 3).

Conclusions:

❖ The analysis of the Energy Dispersive X-ray (EDX) examination showed that the alloying elements of INCONEL 718 on the uncut surface do not change during Nitrogen gas (N_2) assisted laser beam with 13 bar pressure and 2.4 to 4.5 kW range power laser cutting system.

❖ Due to the high surface roughness, which ranges from 32.5 µm to 56.8 µm, laser beam cutting for straight cuts is not an appropriate machining technique to be used in the production 2 mm in thickness INCONEL 718 sheet material.

❖ The significant improvement in surface quality of zigzag cut of INCONEL 718 sheets, each 2 mm thick with Nitrogen gas (N_2) assisted laser beam in compared with straight cut. The Surface roughness was measured at three distinct places, ranging from 0.0978 µm to 0.550 µm.

❖ It has been demonstrated that there are significant hardness differences in both the built plane and the build direction of Inconel 718 as built. The harder it becomes as the number of revolutions rises. Although INCONEL 718's true hardness is between 40 and 45 HRC, the sheet's initial hardness was just 37 HRC. As the number of revolutions rises, the hardness increases from 37 HRC to 44 HRC. Grain refining results from compression caused by the sheets' increasing load. The hardness value rises because of grain refining.

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